# Zeolite Membrane Reactor for Pre-Combustion Carbon Dioxide Capture

*Jerry Y.S. Lin*

**Arizona State University**

**DOE Award:**

**DE-FE0026435**

**Project Kick-Off Meeting**

**January 22, 2016**
**Pittsburgh, Penn**

# Outline

- Background slides on the project team
- Project Objectives
- Technical Approach
- Project Structure/Task Descriptions
- Schedule
- Budget
- Risks
- Milestones
- Success Criteria

Background

Project Objectives

# Overview

## Timeline

- Project start date:
  **Oct.1, 2015**
- Project end date:
  **Sept.30, 2018**
- Budget Periods:
  **I: 10/1/2015-3/31/2017**
  **II: 4/1/2017-9/31/2018**

## Research Area

2B2: Bench-Scale Pre-Combustion $CO_2$ Capture Development and Testing

## Budget

- Total project funding
  - DOE **$2,471,557**
  - Cost-share: **$620,527**
  - Total**: $ 3,092,084**
- Funding for BP I:
  - DOE **$1,274,869**

## Partners

- Arizona State University
- University of Cincinnati
- Media and Process Technology, Inc
- Nexant, Inc.

# Project Teams

| Team | PI or Co-PI | Expertise |
|---|---|---|
| Arizona State University | Jerry Y.S. Lin | Inorganic membranes for gas separation and membrane reactors; adsorption and energy storage. Co-developer of the zeolite membrane reactor technology |
| University of Cincinnati | Junhang Dong | Zeolite membranes, fuel cells, and co-development of the zeolite membrane reactor technology |
| Media and Processes Technology Inc (MPT) | Rich Ciora and Paul Liu | Private company commercializing inorganic membranes for separation and chemical reaction processes |
| Nexant, Inc. | Gerald Choi | Private engineering consultant company specializing in advanced energy generation analysis, integration and techno-economic analysis |

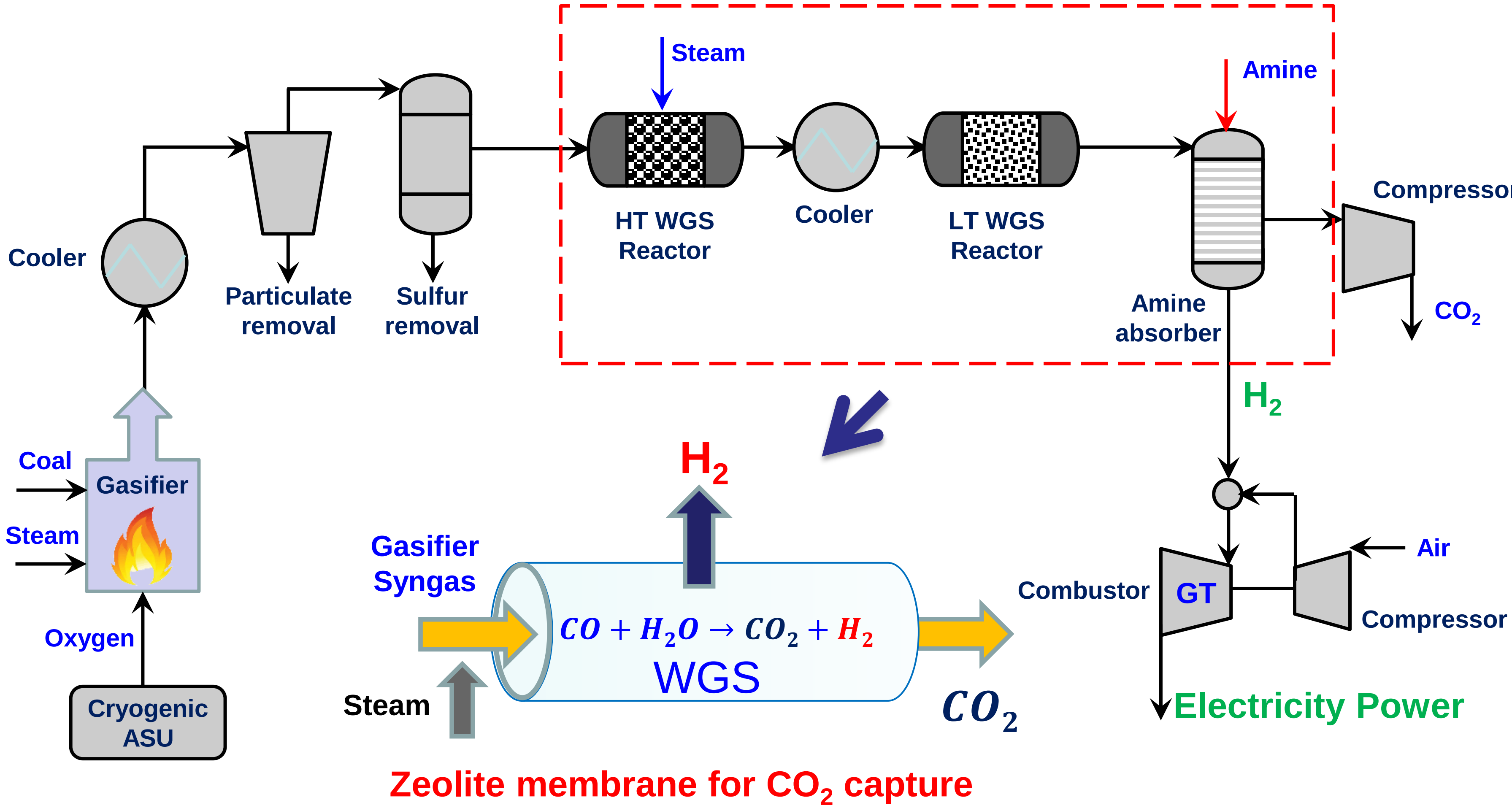
# Project Objectives

To demonstrate a bench-scale zeolite membrane reactor for WGS reaction of coal gasification gas for hydrogen production at capacity equivalent to 10 kW IGCC power plant,

To evaluate the performance and cost-effectiveness of this new membrane reactor process for use in 550 MW coal-burning IGCC plant with $CO_2$ capture.

# Technical Approach

# Zeolite Membrane Reactor for Water-Gas Shift Reaction for $CO_2$ Capture

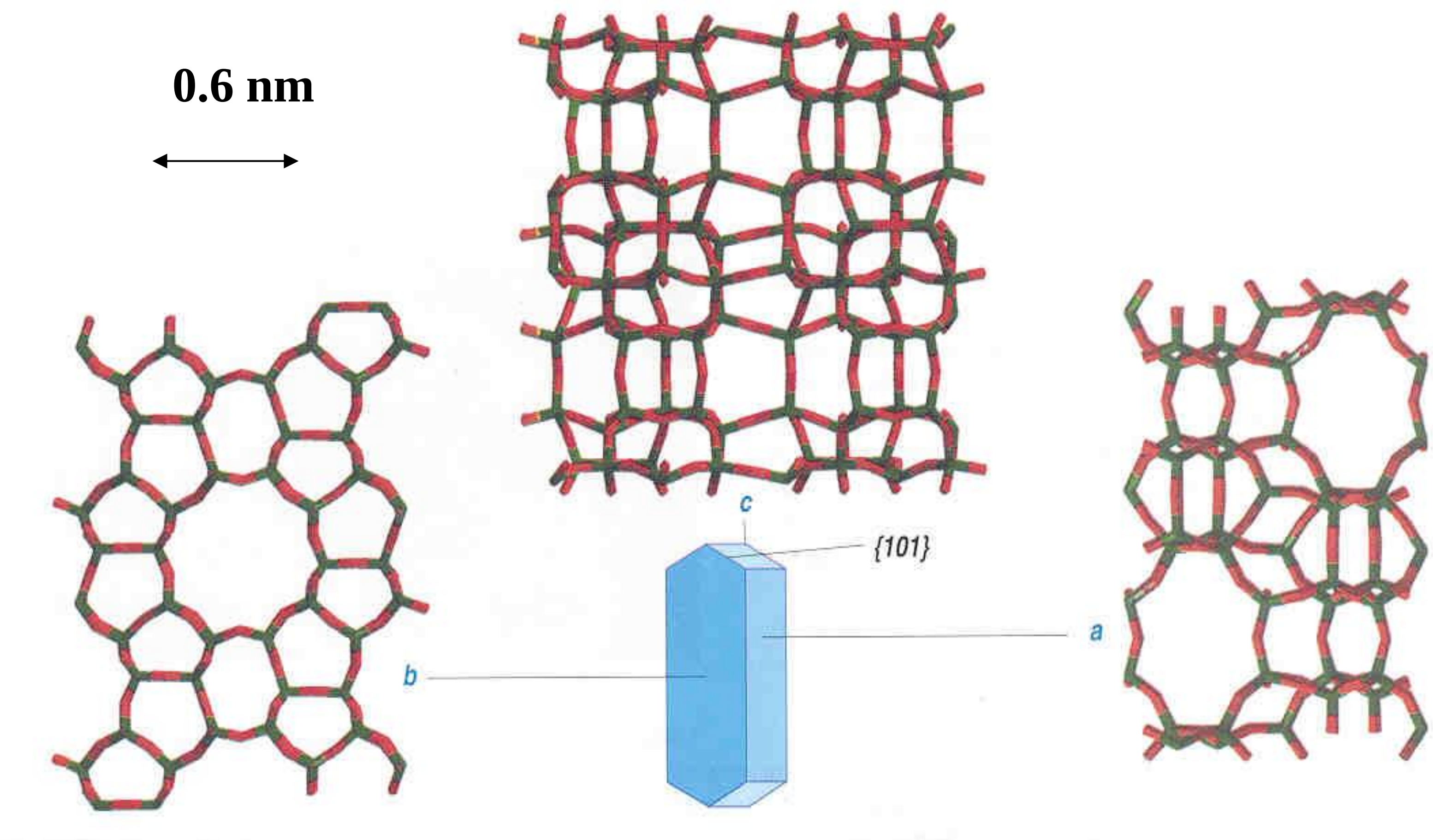



Zeolite Membrane Requirements:

- Operate at 350-550°C
- Chemically stable in $H_2S$, thermally stable at ~400°C
- Hydrogen permeance ~ $2 \times 10^{-7}$ mol/m$^2$.s.Pa (GPU)
- Hydrogen selectivity ~ 50

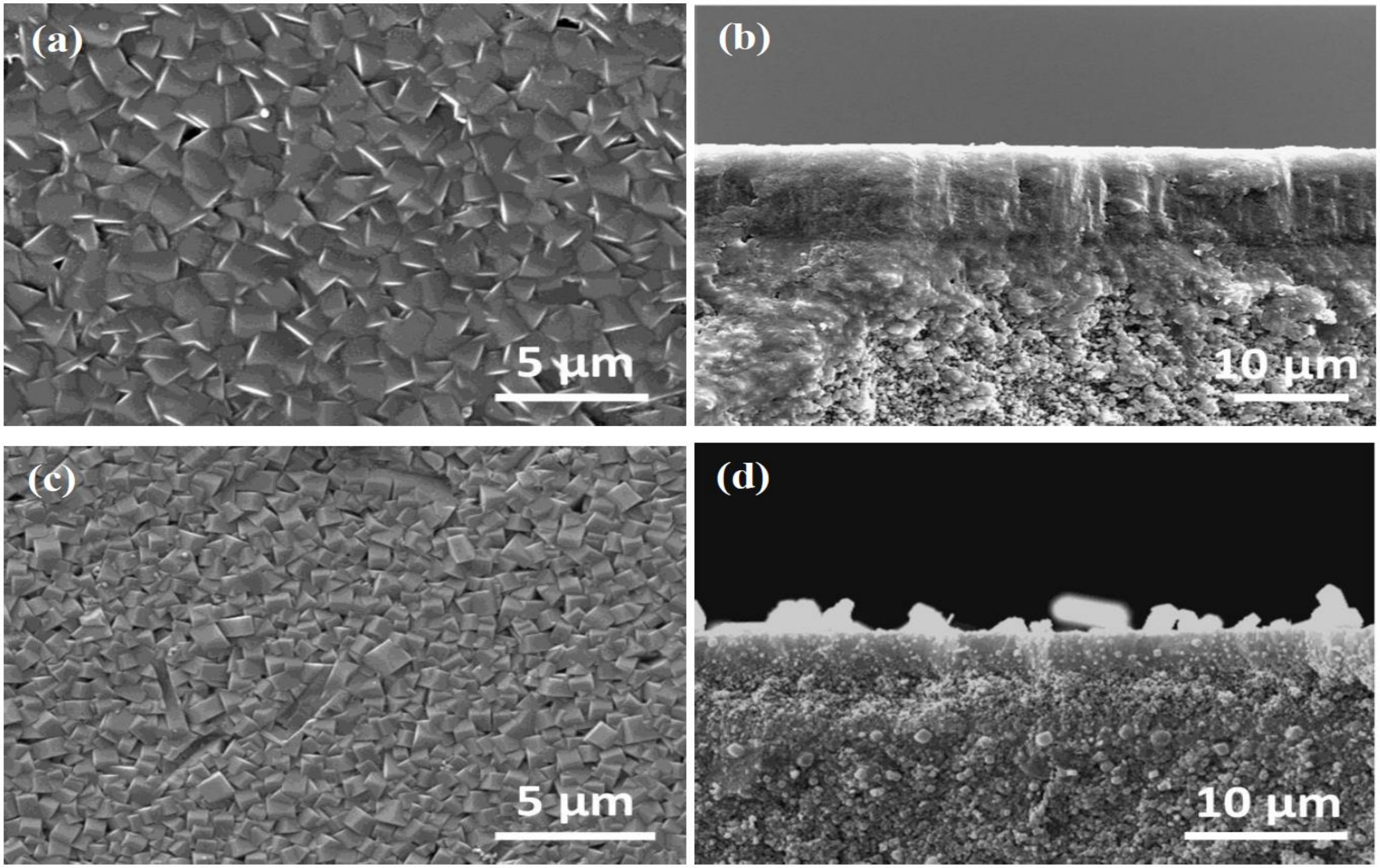
# MFI Type Zeolite

Structure of MFI type Zeolite (ZSM-5 or Silicalite)



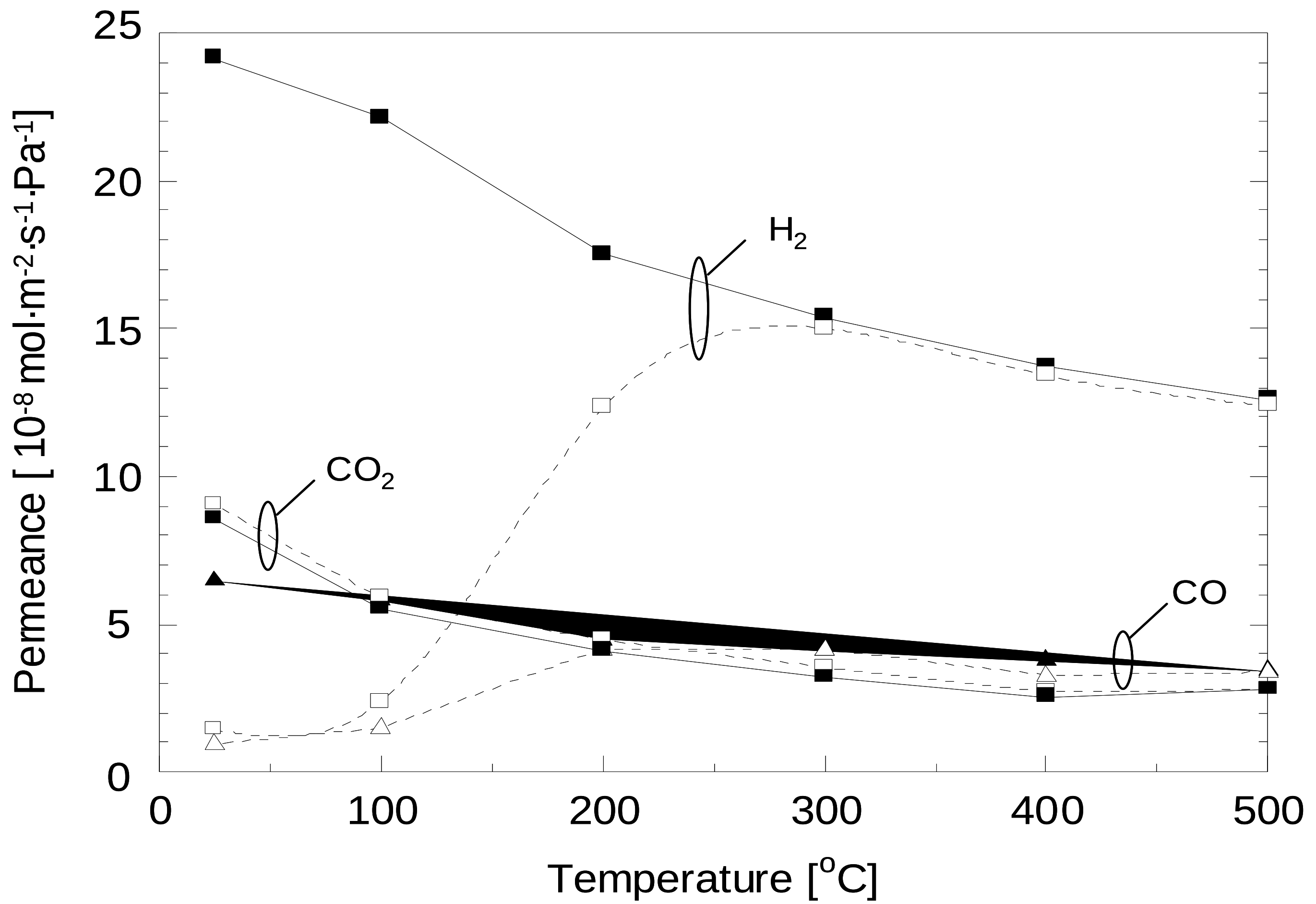

Highly chemically and thermally stable (up to 700$^{o}$C)

# MFI type Zeolite Membrane




*Surface and cross-section SEM images of (a, b) templated synthesized random oriented MFI membrane, (c, d) template-free synthesized random oriented MFI membranes (from Lin lab)*

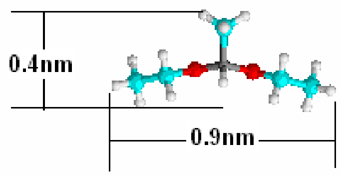
# MFI Zeolite Membrane for Hydrogen Separation

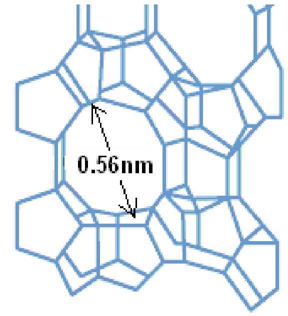



*Temperature dependence of gas permeances for MFI zeolite membrane (closed symbols on solid line: gas permeances for single permeation, open symbols on broken line: those for ternary-component gas separation), feed gas composition ($H_2$:CO:$CO_2$=1:1:1, $P_{up}$: 300 kPa, $P_{down}$: 100 kPa)(from Lin Lab)*

# CVD Narrowing Zeolitic Pores to Further Improve Selectivity

methyldiethoxysilane
(MDES)

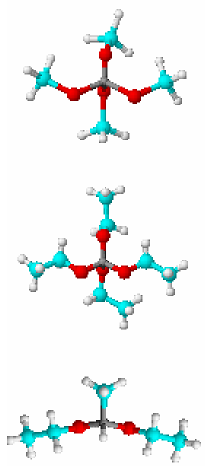


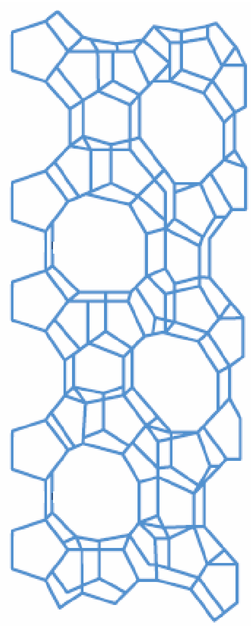




TMOS
0.89nm

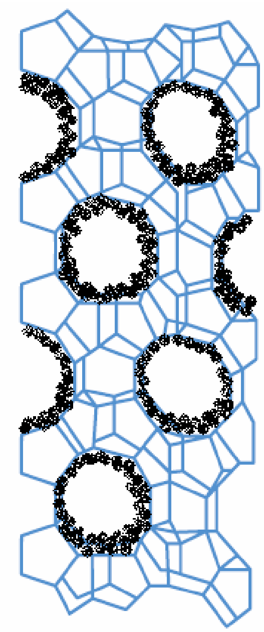
TEOS
0.95nm

MDES
$0.4 \times 0.9$nm

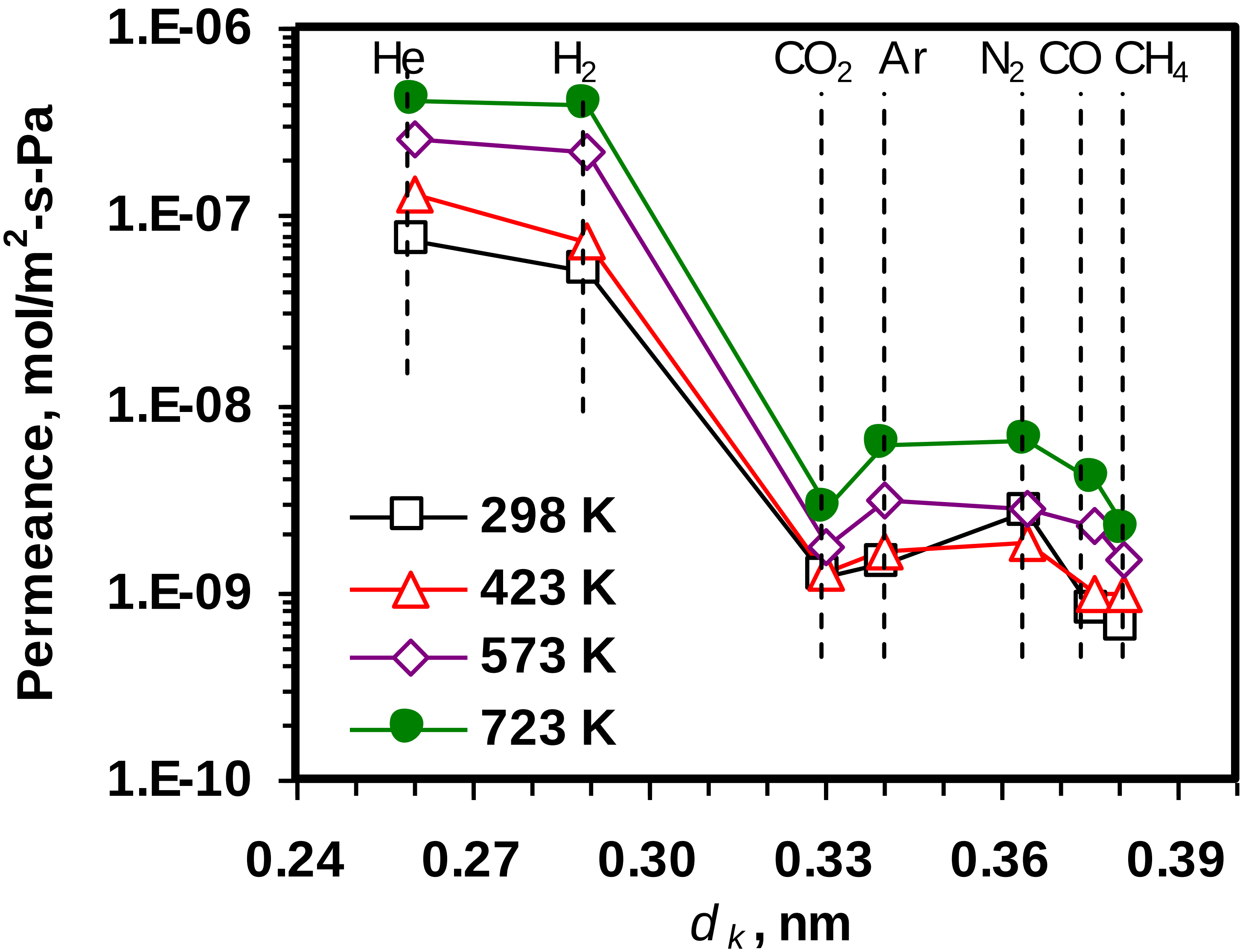




**On stream CVD**



# Single Gas Permeance of a CVD Modified Tubular MFI Zeolite Membrane



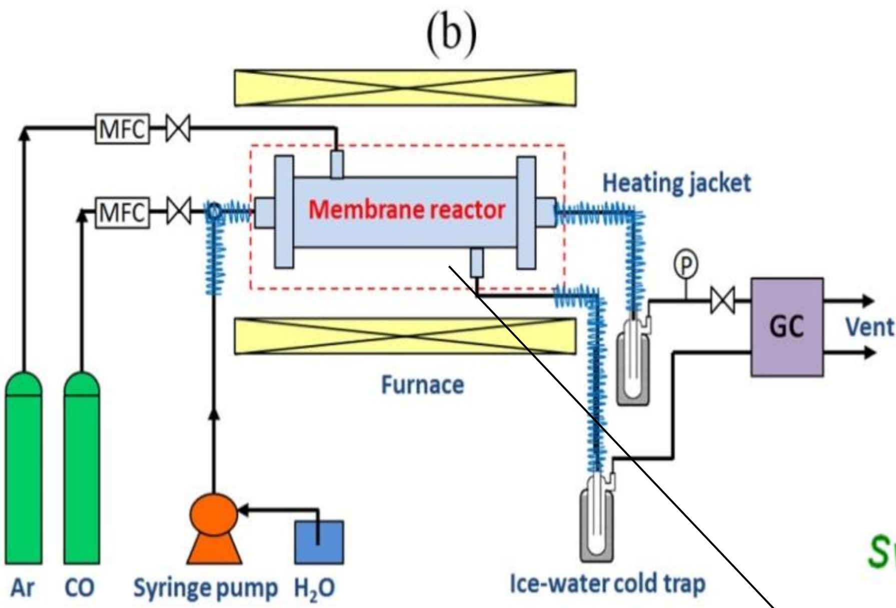

CVD modified tubular zeolite membrane exhibits molecular sieving properties (from Dong Lab)

# Mixture Permeation/Separation Properties for CVD Modified MFI Zeolite

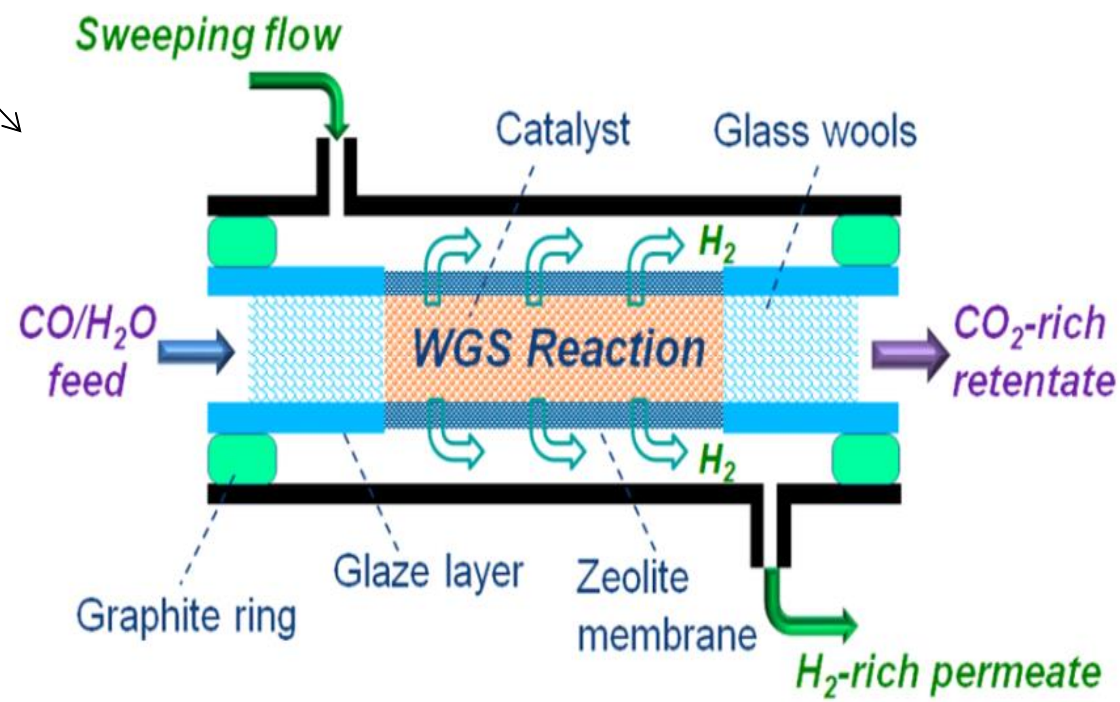
| Parameter | Value |
|---|---|
| $H_2$ Permeanace in (mol/m$^2$.s.Pa) | $1\text{-}4 \times 10^{-7}$ |
| $H_2$ Permeanace in GPU | 300-1200 |
| $H_2/CO_2$ selectivity | 20-140 |
| $H_2/CO$ selectivity | 50-200 |
| $H_2/H_2O$ selectivity | 120-180 |
| $H_2/H_2S$ selectivity | 100-180 |

*With equal-molar feed of $H_2$, $CO_2$, CO and $H_2O$ at 500$^o$C and 2 bar feed (Lin and Dong Labs)*

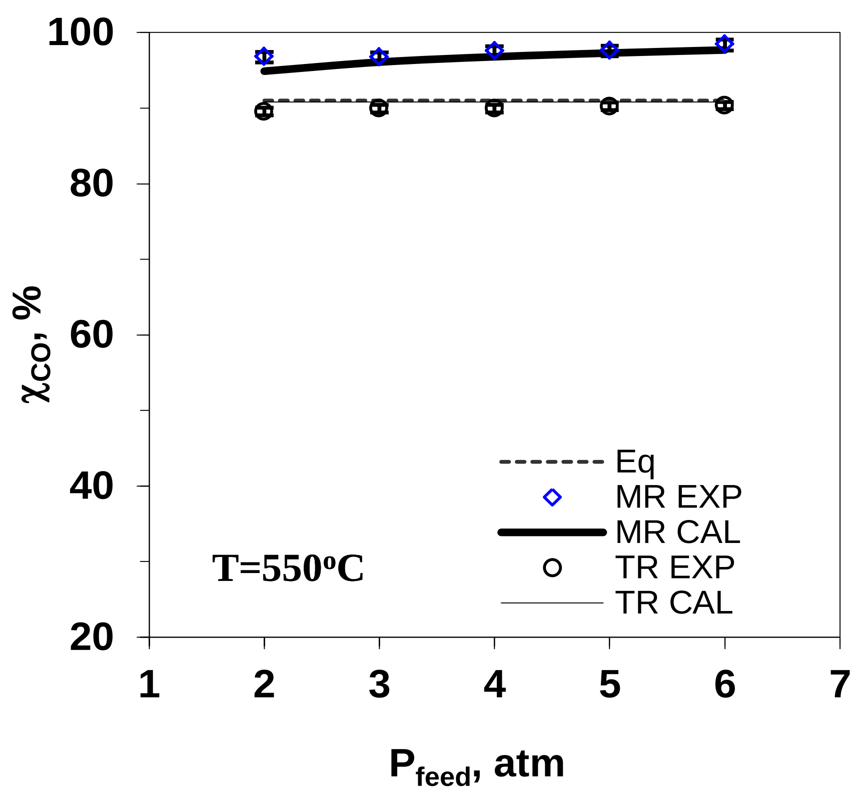
# Lab Scale Tubular Membrane Reactor



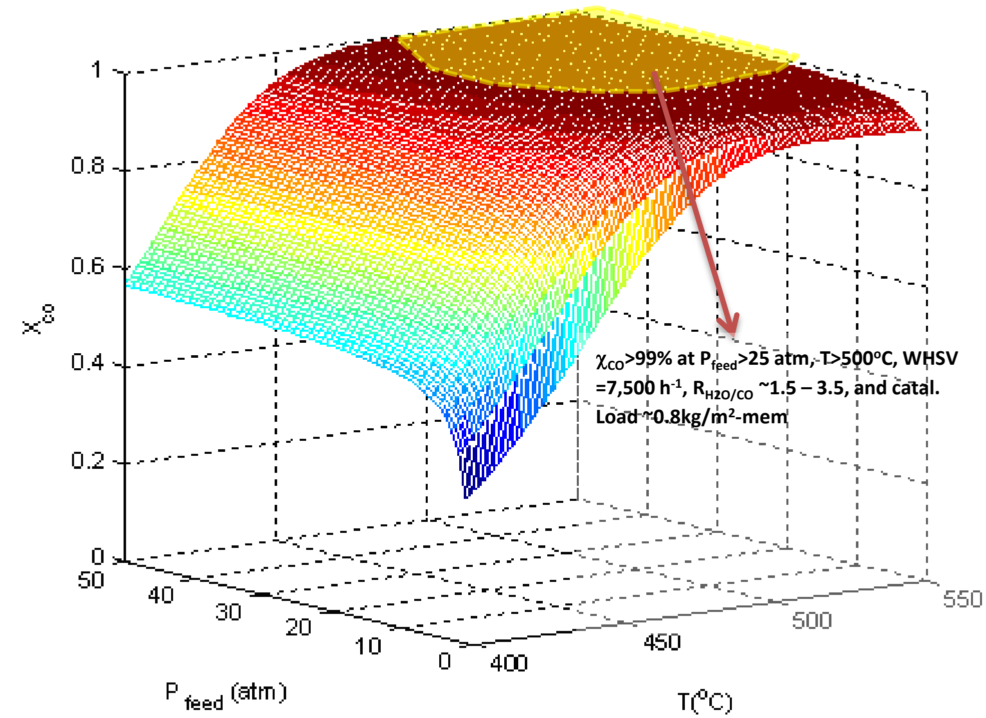

*for testing separation performance and water gas shift reaction of zeolite membrane tube with gas mixture feed WGS reaction conditions (from Lin Lab)*



# WGS in Lab Scale Tubular Membrane Reactor

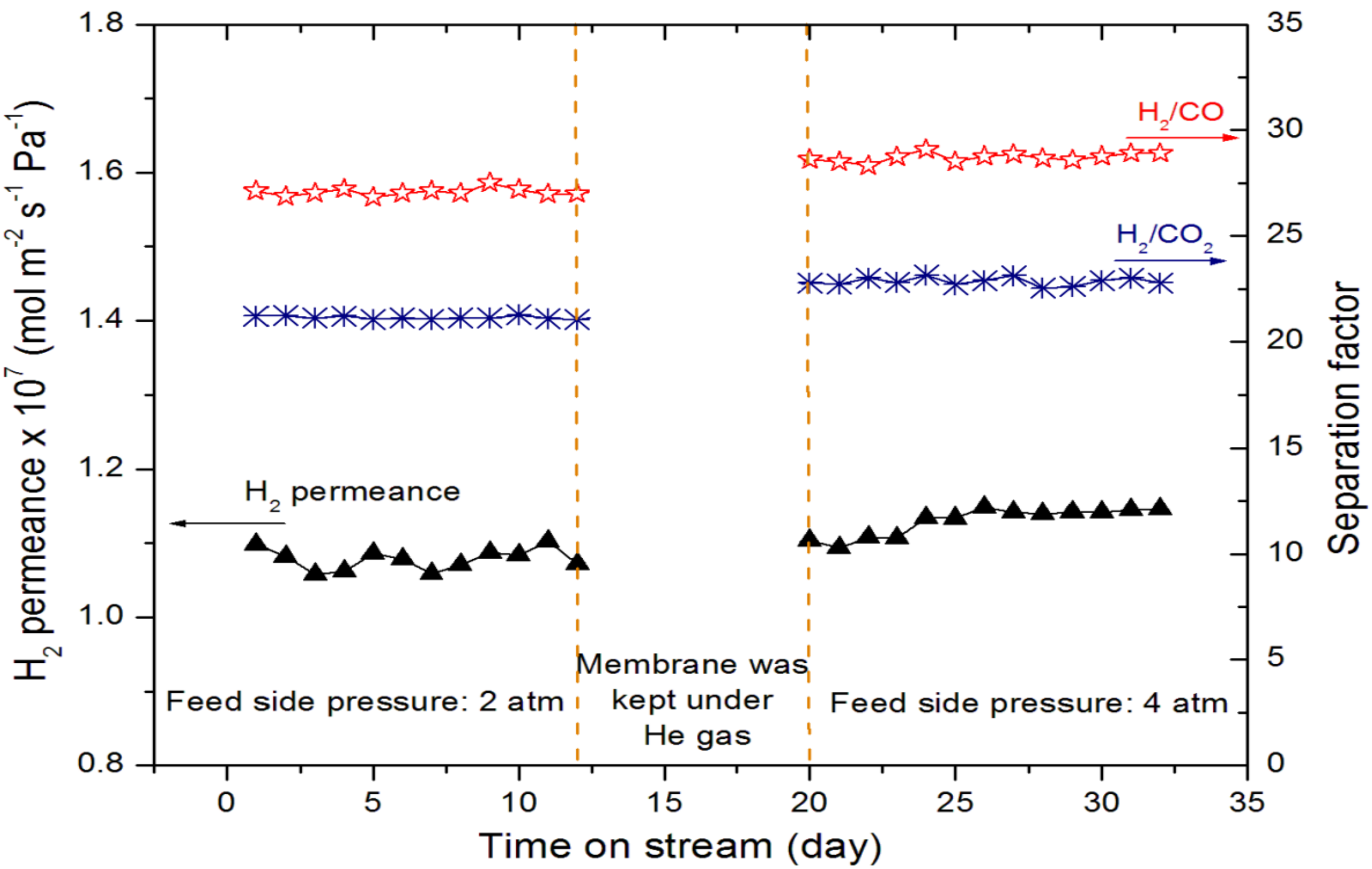



*Experimental and simulated CO conversion ($\chi_{CO}$) of the zeolite membrane reactor (**MR**) and traditional fixed-bed reactor (**TR**) (WHSV=7,500 $h^{-1}$, $R_{H2O/CO}$=3.4,  Sweep($N_2$)= 20 $cm^3$/min; $P_{permeate}$= 1 bar, T=550ºC (from Dong Lab)*



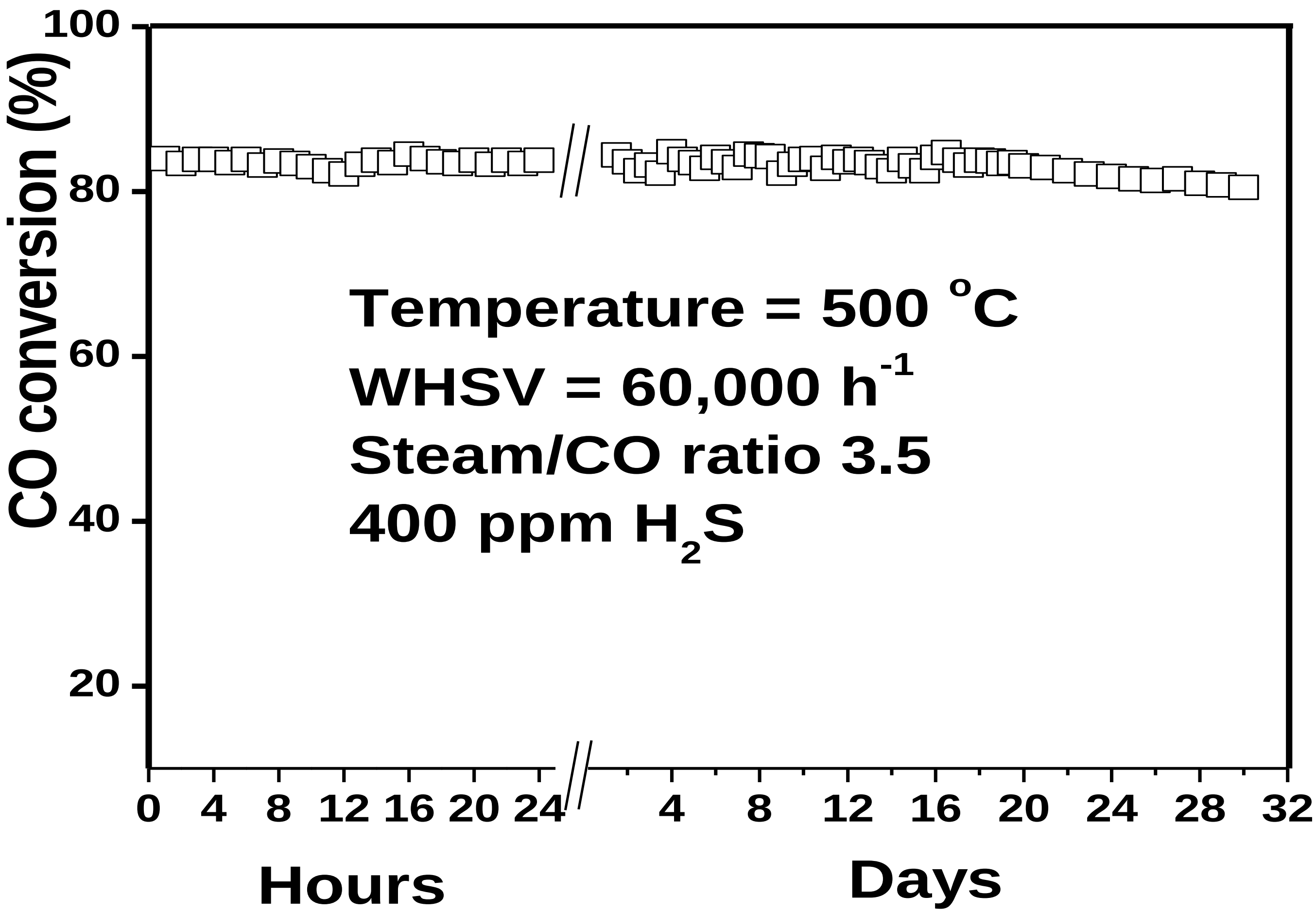

*Modeling of lab-scale zeolite membrane reactor for CO conversion as a function of reaction temperature and pressuring using the experimentally determined parameters (from Lin Lab)*

# Stability under WGS Reaction Conditions – Membrane Separation Results




*Gas composition on feed side:* ***$H_2$: $CO_2$: $H_2O$: CO = 1:1:1:1****, with the presence of* ***400 ppm $H_2S$*** *at 500°C, total gas flow rate: 80 ml·min$^{-1}$(STP), sweeping helium gas flow rate: 20 ml·min$^{-1}$ (STP), permeate side pressure: 1bar (from Lin Lab)*

# Stability under WGS Reaction Conditions – WGS Reaction Results




Long term time on stream stability experiments over Fe/Ce catalyst for 30 days in the presence of 400 ppm of sulfur (from Dong Lab)

# Proposed Bench-Scale Zeolite Membrane Rectors for WGS

| | Unit | Measured | Projected Performance |
|---|---|---|---|
| **Materials Properties** | | | |
| Materials of Fabrication for Selective Layer | | Modified MFI zeolite | |
| Materials of Fabrication for Support Layer (if applicable) | | Macroporous alumina with or without a macroporous yttria stabilized zirconia layer | |
| Nominal Thickness of Selective Layer | μm | 5-10 | 1-5 |
| Membrane Geometry | | disk and tube | Small OD tube |
| Max Trans-Membrane Pressure | bar | 7 | 30 |
| Hours tested without significant degradation | | 600 hours with 400ppm $H_2S$ | 1000 |
| **Membrane Performance** | | | |
| Temperature | °C | ≥500 | ≥500 |
| Pressure Normalized Flux for Permeate ($CO_2$ or $H_2$) | GPU or equivalent | 1000 | 1200 |
| $CO_2/H_2O$ Selectivity | - | / | |
| $CO_2/N_2$ Selectivity | - | / | |
| $CO_2/SO_2$ Selectivity | - | / | |
| $CO_2/H_2$ Selectivity | - | / | |
| $H_2/CO_2$ Selectivity | - | 140 | 140 |
| $H_2/H_2O$ Selectivity | - | 100 | 100 |
| $H_2/H_2S$ Selectivity | - | 180 | 180 |
| Type of Measurement (Ideal or mixed gas) | - | mixture | mixture |
| **Proposed Module Design** | | Single tube | Multiple tubes |
| Flow Arrangement | - | Co-current flow | |
| Packing Density | $m^2/m^3$ | 40-60 | |
| Shell-Side Fluid | - | Sweep with steam at 1 bar | |

# Design Characteristics for Bench Scale Zeolite Membrane Reactor for WGS with Coal Gas

| Item | Value | Unit |
|---|---|---|
| IGCC electricity production power | 10 | kW |
| Efficiency of IGCC | 0.4 | |
| Higher Heating Value of Coal | 29,712 | kJ/kg |
| Coal Consumption Rate (mass)/s | $8.4 \times 10^{-6}$ | kg/s |
| Carbon Content in Coal (mass fraction, dry basis)# | 0.696 | |
| Rate of CO in Syngas | $4.15 \times 10^{-2}$ | mol/s |
| Rate of $H_2$ in Syngas | $3.01 \times 10^{-2}$ | mol/s |
| Rate of total $H_2$ after WGS | $7.16 \times 10^{-2}$ | mol/s |
| Total $H_2$ production daily mas rate | 12.2 | kg/day |
| Total $H_2$ production volumetric flow rate | 96 | L/min |
| $H_2$ permeance for zeolite membrane | $3.04 \times 10^{-7}$ | mol/m$^2$.s.Pa |
| Average feed $H_2$ partial pressure | 1.0 | MPa |
| Average permeate $H_2$ pressure | 0.1 | MPa |
| Total membrane area required | 0.27 | m$^2$ |
| Membrane tubule dimension (ID x OD x L)* | $0.35 \times 0.57 \times 25$ | cm |
| Surface area per tube (outer) | $4.5 \times 10^{-3}$ | m$^2$/tube |
| Total number of zeolite membrane tubes required | 60 | / |
| Total number of tubes for the proposed bench scale WGS reactor | 70 | / |

# Assume 85% Carbon Converted to CO,

* The actual tube length is 35 cm with 5-cm end region for seals in both ends

# General Approach to Scaling up WGS Zeolite Membrane Reactor

Single-tube zeolite membrane reactor: study WGS up to 30 atm by experiments and modeling

↓

Intermediate-scale membrane reactor:  7 to 14 tube membrane module, and WGS reaction in the intermediate-scale reactor

↓

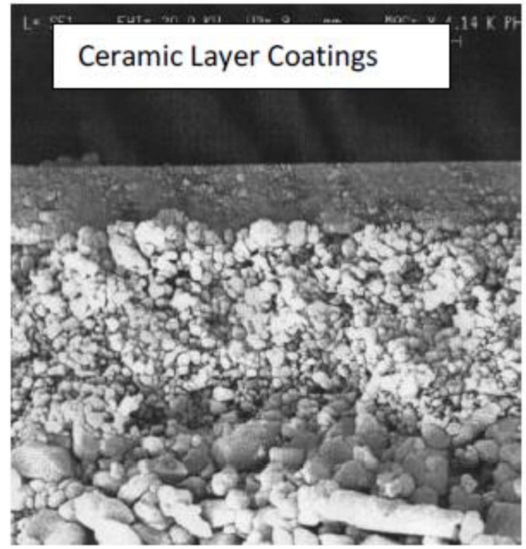
Bench-scale membrane reactor:  70 tube membrane module, and WGS reaction in the bench-scale membrane reactor

→ Membrane reactor in IGCC with $CO_2$ capture - process design and techno-economic analysis

# Fabrication of Tubular Supports for Zeolite Membranes

- Tubular porous α-$Al_2O_3$ supports of 3.5 mm ID and 5.7 mm OD;
- Base has pore size of ca. 0.5µm, prepared by extrusion;
- Top-layer: 5 to 100nm pore, prepared by slip casting
- Can withstand transmembrane pressures in excess of 100 bars (10 MPa).

MPT Tubular Ceramic Supports



Ceramic Layer Coatings

MPT Commercial Bundles for Liquid Phase Separations

MPT Experimental Full Ceramic Bundles for High Temperature High Pressure Gas Phase Separations

# Fabrication of Zeolite Membranes

In-situ synthesis of MFI film on multiple support tubes (35 cm long, 3.5 mm ID and 5.7 mm OD) on horizontally rotating synthesis reactor housing 61 tubes

↓

Formation of single and multiple tube zeolite membrane module

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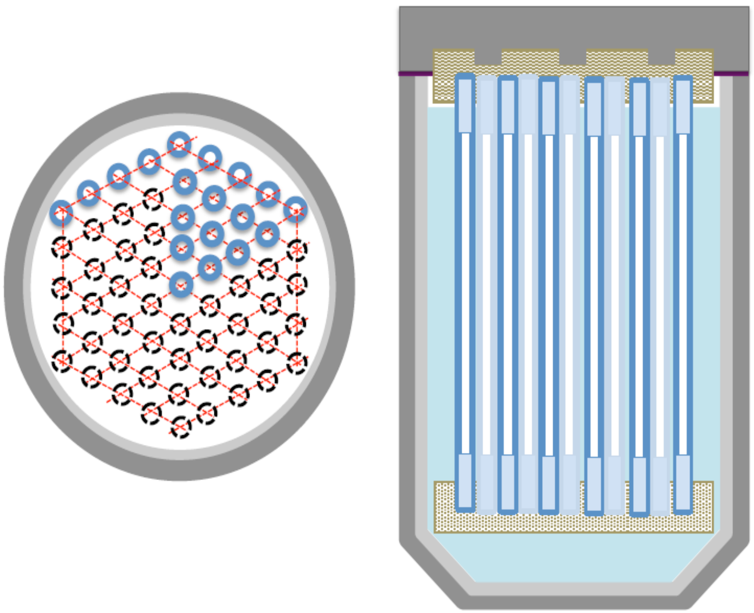
CVD modification of the single or multiple tube zeolite membrane in membrane modules with simultaneous measurement of $H_2/CO_2$ separation characteristics



horizontally rotating multi-tube zeolite membrane synthesis reactor

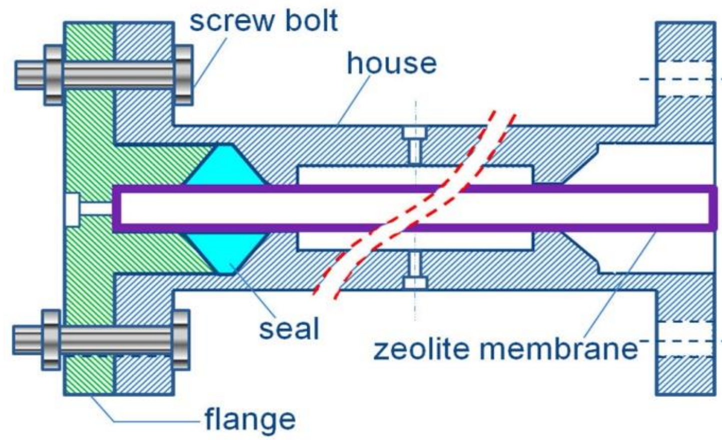
# Experimental and Modeling Studies of WGS in Membrane Reactors at High Pressures

Design of reactor for longer tube (12.5 and 25 cm) and higher pressure (30 bar)

Synthesis of stable, $H_2S$ and coking resistant ceria based WGS catalyst

$H_2$ separation and WGS reaction experiments

Modeling $H_2$ separation and WGS reaction in single tube and multiple tube zeolite membrane reactor




*Schematic illustration of the ends structure of the tubular membrane module to be used with radially compressed graphite seals (not to scale)*

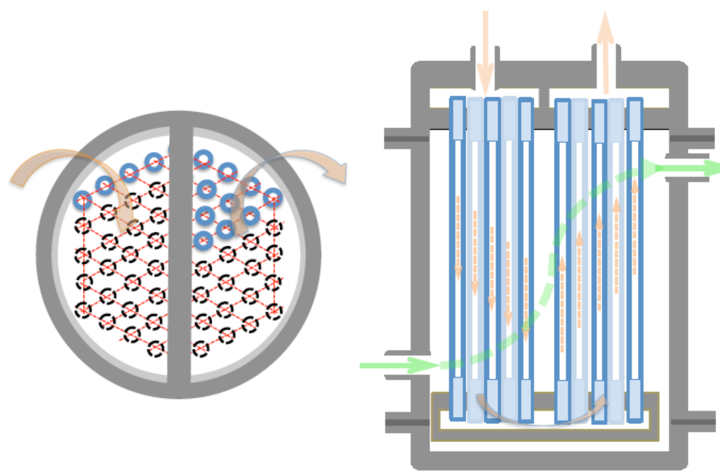
# Design, Fabrication and Testing of Bench Scale Membrane Modules

**A-Module Design and Fabrication**

*MPT's multiple tube bundle with full ceramic potting and tube sheet and stainless steel housing*

Thorough re-rating and possible redesign of the module to confirm its potential for safe operation at the desired temperature up to 600°C and pressure up to a potential of 55 bar

*Alternative free-end membrane module to handle thermal stress*



# Design, Fabrication and Testing of Bench Scale Membrane Modules

## B- Modeling WGS and $H_2/CO_2$ Separation in the Membrane Modules

Modeling WGS in multiple channel membrane reactor using permeation and kinetic data obtained in the single-tube reactor

## C-Preliminary WGS Membreane Reacto Testing with Multiple-Tube Bundles

Testing $H_2$ separation at high pressure and temperature on the intermediate-scale zeolite membrane module (7-14 tubes)

WGS catalyst fabrication (upto 6 kg)

Catalyst packing, gas and pressure handling and separation performance of bench-scale zeolite membrane module

# Membrane and WGS-Reactor Testing at National Carbon Capture Center

**Composition and conditions of syngas at NCCC Site**

| Composition or Temperature and pressure | NCCC Raw Syngas | Desired syngas for this project |
|---|---|---|
| $H_2$ | 5-7% | 26% |
| CO | 9-11% | 27% |
| $CO_2$ | 9-11% | 14% |
| $N_2$ | 69-74% | 0 |
| $CH_4$ | 0.9-1.2% | 0 |
| $H_2O$ | ~0 | 34% |
| $H_2S$ | 400 ppm | 50 ppm (0.56%)# |
| Pressure | 180-190 psig | 285 psig (20 bar) |
| Temperature | 500-550 F | 350-550$^o$C |

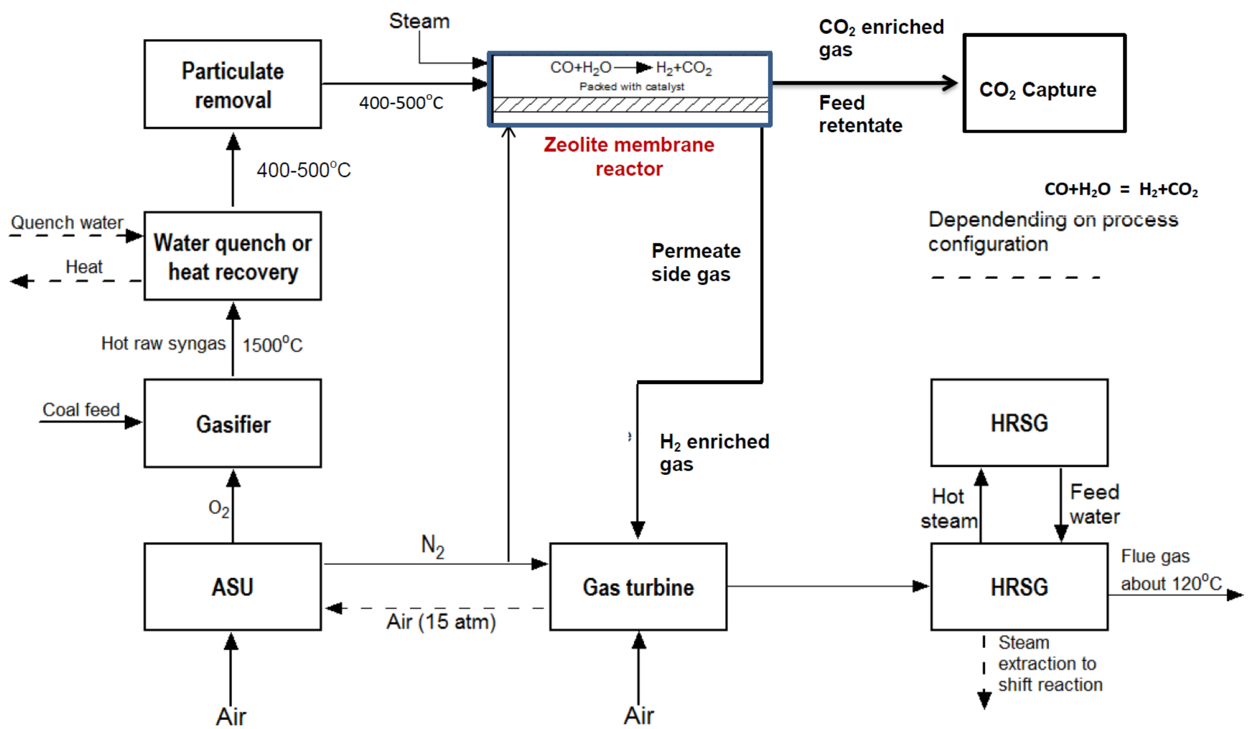
*Picture of an MPT membrane test skid at NCCC for testing hydrogen separation by carbon molecular sieve membrane modules with shifted syngas.*

# Process Design, Economical Analysis and EH&S Risk Assessment

*Conditions for Cost Estimation of Membrane Reactor (550 MW Coal-Burning IGCC Power Plant)*

| Parameters | Conditions |
|---|---|
| Coal type | Illinois 6# |
| Coal feed | slurry |
| Gasifier type | GE gasifier |
| Coal Consumption Rate | 220,904 kg/hr |
| Carbon Content in Coal (dry basis) | 0.70 |
| Rate of CO in Syngas | 2,296mol/s |
| Rate of $H_2$ in Syngas | 2,187 mol/s |
| Pressure of coal gas to WGS reactor | 3 MPa |
| Temperature of coal gas to WGS reactor | 400-550ºC |

*Preliminary Proposed IGCC Process with $H_2$ Separation using MFI Zeolite Membrane and Carbon Dioxide Capture*



# Project Structure
# &
# Task Descriptions

# Scope of work

1) **Scaling up a zeolite membrane reactor from lab-scale to bench-scale for combined WGS reaction and $H_2$ separation**

2) **Conducting a bench-scale study using this zeolite membrane reactor for hydrogen production for IGCC with $CO_2$ capture.**

Goal is to demonstrate effective production of $H_2$ and $CO_2$ capture by the bench-scale zeolite membrane reactor from a coal gasification syngas at temperatures of 400-550°C and pressures of 20-30 atm:

- Bench-scale zeolite membrane reactor: 70 zeolite membrane tubes of 3.5 ID, 5.7 OD and 25 cm L(active)

- A system producing $H_2$ at rate of about 10 kg/day, equivalent to a 10-$kW_{th}$ IGCC power plant

# Task Description

## Task 1.0 Project Management and Planning

## Budget Period 1 (first 18 months)

## Task 2.0 Experimental Study on WGS in Lab-Scale Tubule Zeolite Membrane Reactor (ASU)

Studying WGS in a single tube zeolite membrane reactor at high pressures to provide guidance for the design of bench-scale zeolite membrane reactor.

- **Subtask 2.1 Setting up high pressure WGS membrane reactor**
- **Subtask 2.2 Evaluating performance of WGS catalyst**
- **Subtask 2.3 Experiments on WGS in lab-scale membrane**
- **reactor**

## Task 3.0 Modeling and Analysis for WGS in Zeolite Tubule Membrane Reactor (ASU)

- Developing model for WGS in zeolite membrane reactor
- Analyzing

    single-tube membrane reactor

    multiple-tube membrane reactor

# Task Description (cont'd)

## Task 4.0 Optimizing Tubular Support Fabrication (MPT)

Fabricating tubule supports with desired chemical, thermal, and mechanical stability for coating the $H_2$-selective MFI type zeolite membrane layers and for application in the demanding coal-derived gasifier syngas environment.

Support tube dimension: 3.5 mm ID, 5.7 mm OD, and 35 cm (longer than the for zeolite membrane reactor for sealing purpose)

## Task 5.0 Optimizing Zeolite Membrane Synthesis Methods (UC)

Identifying optimum conditions for secondary growth synthesis and CVD modification of MFI zeolite membranes with minimized thickness and optimized silica/aluminum (Si/Al) ratio using the conventional heating method on the longer support tubes.

# Task Description (cont'd)

## Task 6.0 Scaling up Synthesis of High Quality Zeolite Membranes (UC)

Scaling up zeolite membrane synthesis and modification methods in order to make a large quantity of zeolite membrane tubes of consistent quality.

**Subtask 6.1 Identifying conditions to make multiple zeolite membrane tubes per batch:**

**Subtask 6.2 Preparing 20-30 zeolite membrane tubes for Intermediate-scale membrane reactor module**

## Task 7.0 Design and Fabrication of Zeolite Membrane Bundles and Modules (MPT)

Design and fabrication of zeolite membrane full ceramic potted bundles and corresponding modules, testing these bundles under a range of challenge conditions:

- Single-tube membrane module
- 7-14 tube membrane module

# Task Description (cont'd)

**Task 8.0. Testing Zeolite Tube Bundles under Gasifier Conditions Including Membrane Reactor Configuration (MPT)**

Testing hydrogen separation of the single tube and intermediate scale multiple tube zeolite membrane bundles prepared as a product of the Task 7.0 activities

**Task 9.0. Establishing Conceptual Process Design, Performance Model and Preliminary Techno-Economic Analysis of WGS Zeolite Membrane Reactor Technology (Nexant)**

Establishing a conceptual process design and performance model, and performing a preliminary techno-economic analysis of the WGS zeolite membrane reactor technology for IGCC application with pre-combustion $CO_2$ capture

# Task Description (cont'd)

## Budget Period 2 (second 18 Months)

### Task 10.0 Modeling and Analysis of WGS in Bench-Scale Zeolite Membrane Modules for WGS (ASU)

**Subtask 10.1 Modeling and analysis of WGS in multi-tube membrane reactor module:** developing a model for WGS in the bench-scale zeolite membrane reactor

**Subtask 10.2 Optimization of operation conditions for WGS in zeolite membrane module:** identifying operation mode and conditions that will give the desired $CO_2$ capture (>90%) and retentate $CO_2$ concentration (>95%).

### Task 11.0 Fabrication of Large Quality Tubule Supports (MPT)

Fabricating 300-500 support tubules with nominal dimensions of 3.5 mm ID, 5.7 mm OD, and 35 cm L.

# Task Description (cont'd)

## Task 12.0 Preparation of Large Quantity MFI Zeolite Tubule Membranes for Bench-Scale Module (UC)

Making a sufficient number of high quality MFI-zeolite membranes for the bench-scale WGS zeolite membrane reactor.

**Subtask 12.1 Identifying conditions for fabrication of large quantity of zeolite membrane tubes:** further adjusting the conditions found in the multi-tube batch synthesis for a larger reactor to prepare 61 zeolite membrane tubes of consistent quality in a single reactor (one batch).

**Subtask 12.2 Fabrication of 200-300 zeolite membrane tubules with desired quality:** produce 200-300 modified MFI zeolite membranes of 3.5 mm ID, 5.7 mm OD, and 35 cm in length (25-cm zeolite membrane section) for constructing the bench-scale zeolite membrane reactor.

# Task Description (cont'd)

## Task 13.0 Design and Fabrication of Bench-Scale Zeolite Membrane Housing (MPT, ASU)

Design and fabrication of the bench-scale housing for the bench scale zeolite membrane bundle for safe operation at the desired temperature up to 600°C and pressure up to a potential of 40 bar.

## Task 14.0 Building Bench-Scale Zeolite Membrane Reactors (MPT, ASU)

Building the bench scale zeolite membrane bundles of 70 zeolite membrane tubules and membrane reactors with catalyst

**Subtask 14.1 Fabrication and evaluation of WGS catalyst for bench-scale WGS reaction**

**Subtask 14.2 Assembling and testing bench-scale zeolite membrane reactor**

**Subtask 14.3. Modification and installation of the bench-scale membrane reactor testing skid**

# Task Description (cont'd)

## Task 15.0 Testing WGS Reaction in Bench-Scale Membrane Reactor (MPT)

Performing experiments on WGS reaction in the bench-scale zeolite membrane reactor at NCCC and to identify conditions for operating the single stage membrane reactor to achieve CO conversion larger than 99.5%, $CO_2$ capture >90%, and $CO_2$ purity >95%, and desired $H_2$ purity and recovery.

## Task 16.0 Process Design, Techno-Economic and EH&S Analyses (Nexant)

Design and process development of WGS membrane reactor and its integration with 550 MW IGCC power plants with $CO_2$ capture.

**Subtask 16.1 Design of Commercial Scale WGS Zeolite Membrane Reactor and Process**

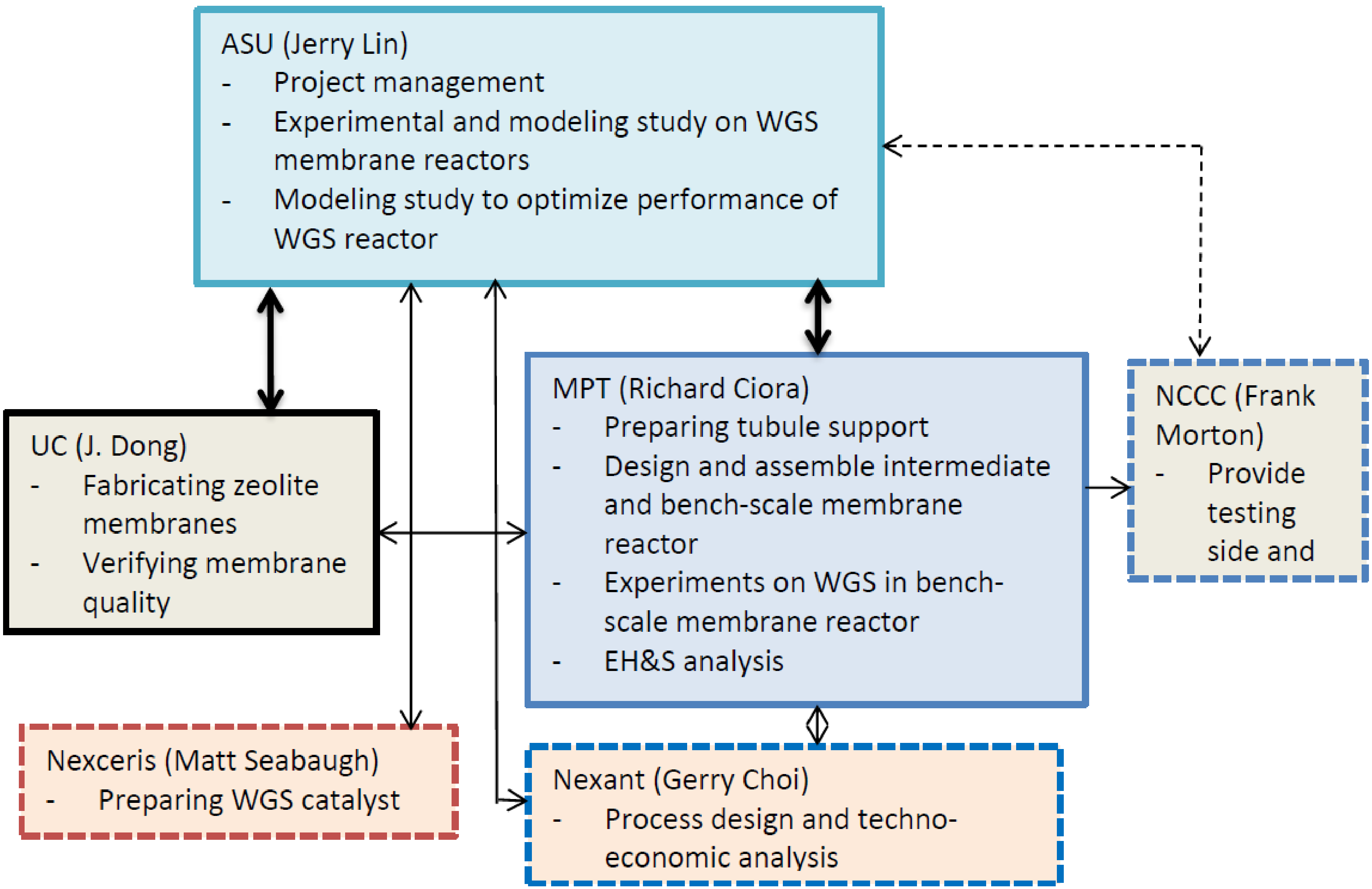
**Subtask 16.2 Updated Techno-Economic Analysis (TEA) of IGCC Plant**

**Subtasks 16.3 Preliminary Technology EH&S Assessment**

# Task Distribution

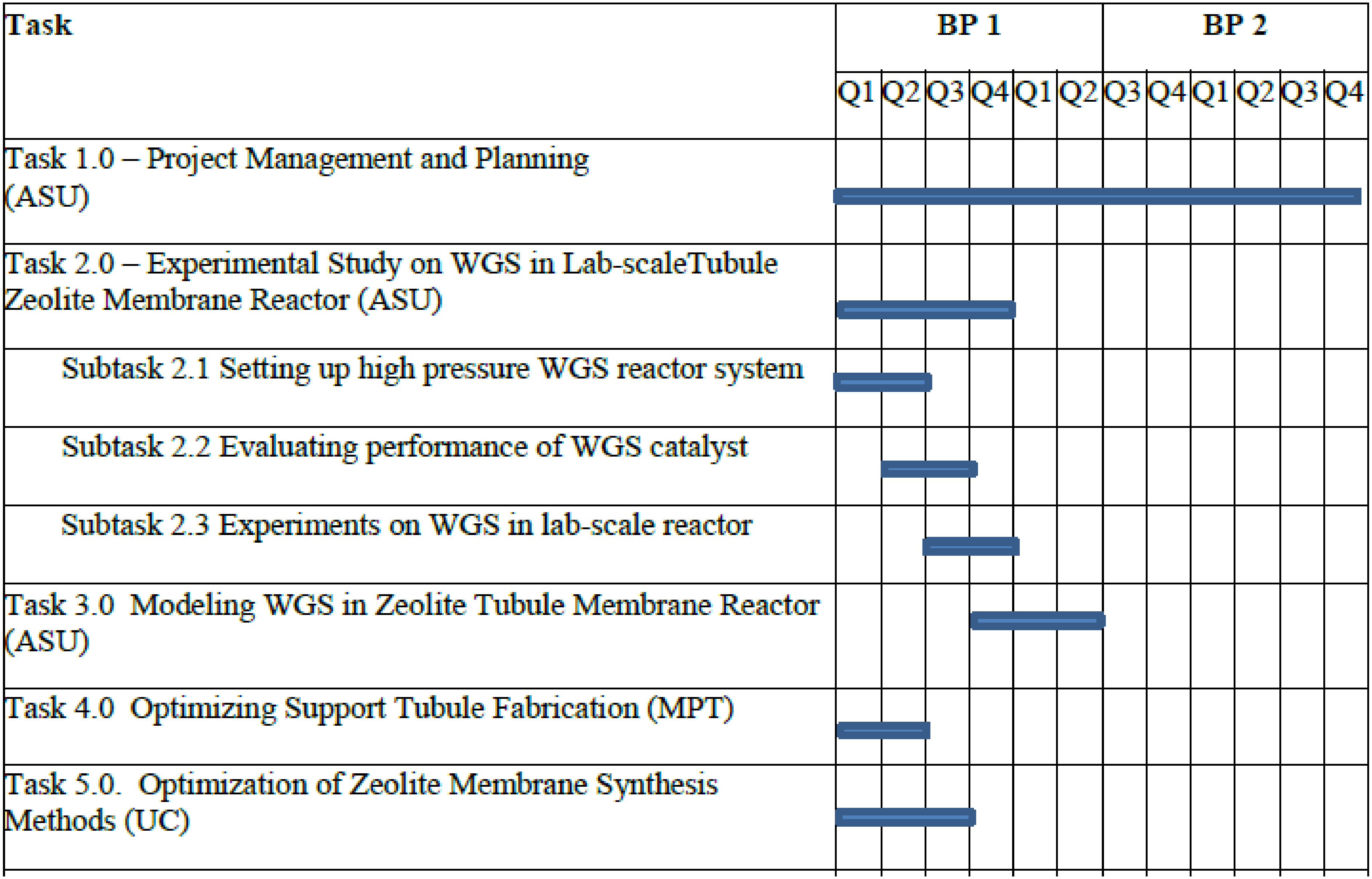
| Team | Task |
|---|---|
| Arizona State University (ASU) | • Project management<br>• Membrane reactor performance study<br>• Predicting membrane reactor scaling up<br>• Catalyst development (with Nexceris)<br>• Design of membrane modules<br>• Identifying bench scale operation conditions |
| University of Cincinnati (UC) | • Developing methods to scale up zeolite tube membrane synthesis and modification<br>• Examining the quality of zeolite membrane tubes and determining gas transport properties of as-synthesized membranes<br>• Fabricating tubular zeolite membranes of large quantity |
| Media and Processes Technology, Inc (MPT) | • Support tube fabrication<br>• Design and fabrications of membrane modules<br>• Assembly and testing bench-scale membrane reactors;<br>• Testing WGS reaction in bench-scale at NCCC site<br>• Process design and environmental health & safety assessment |
| Nesant, Inc | • Process design and techno-economic analysis |

# Management Chart and Material and Information Exchanges



# Schedule and Budget

# Project Schedule



# Project Schedule (Cont'd)

| Task |
|---|
| Task 6.0 Scaling up Synthesis of High Quality Zeolite Membranes (UC) |
| Subtask 6.1 Identifying condition to make 9 zeolite membrane tubes in one batch |
| Subtask 6.2 Preparing 20-30 zeolite membrane tubes Intermediate-scale membrane reactor module |
| Task 7.0 Design and Fabrication of Intermediate-Scale Zeolite Membrane Module (MPT) |
| Task 8.0. Testing Intermediate-Scale Membrane Reactors (MPT) |
| Subtask 8.1 Design and modifying the membrane reactor testing skids (MPT) |
| Subtask 8.2 Assembling and Testing Intermediate-Scale Zeolite Membrane Reactor (MPT/ASU) |
| Task 9.0. Establishing Conceptual Process Design, Performance Model and Preliminary Techno-Economic Analysis of WGS Zeolite Membrane Reactor Technology |

# Project Schedule (Cont'd)

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Task 10.0 Modeling and Analysis of WGS in Bench Scale Zeolite Membrane Modules for WGS (ASU) | | | | | | | | | | | | |
| Subtask 10.1 Modeling and analysis of WGS in multi-tube membrane reactor module | | | | | | | | | | | | |
| Subtask 10.2 Optimization of operation conditions for WGS in zeolite membrane module | | | | | | | | | | | | |
| Task 11.0. Fabrication of Large Quality Tubular Supports (MPT) | | | | | | | | | | | | |
| Task 12.0 Preparation of Large Quantity MFI Zeolite Tube Membranes for Bench-Scale Module (UC) | | | | | | | | | | | | |
| Subtask 12.1 Identifying conditions for fabrication of large quantity of zeolite membrane tubes | | | | | | | | | | | | |
| Subtask 12.2 Fabrication of 200-300 zeolite membrane tubules with desired quality | | | | | | | | | | | | |
| Task 13.0 Design and Fabrication of Bench-Scale Zeolite Membrane Module Housing with Seals (MPT/UC/ASU) | | | | | | | | | | | | |

# Project Schedule (Cont'd)

| |
|---|
| Task 14.0 Building Bench-Scale Zeolite Membrane Reactors (MPT/ASU/UC) |
| Subtask 14.1 Fabrication and evaluation of WGS catalyst for bench-scale WGS reaction (ASU) |
| Subtask 14.2 Assembling and testing bench-scale zeolite membrane reactor (MPT/UC/ASU) |
| Subtask 14.3. Modification and installation of the membrane reactor testing skid (MPT/ASU) |
| Task 15.0 Testing WGS in Bench-Scale Membrane Reactor (MPT) |
| Task 16.0 Process Design, Techno-Economic and EH&S Analyses (MPT) |
| Subtask 16.1 Design of Commercial Scale WGS Zeolite Membrane Reactor and Process (MPT/Nexant) |
| Subtask 16.2 Techno-Economic Analysis (TEA) of IGCC Plant (Nexant) |
| Subtask 16.3 Preliminary Technology EH & S Assessment (MPT) |

# Project Funding Profile

| | Period 1 | | Period 2 | | Total Project | |
|---|---|---|---|---|---|---|
| | 10/01/15-03/31/17 | | 04/01/17-09/30/18 | | | |
| | DOE Share | Cost Share | DOE Share | Cost Share | DOE Share | Cost Share |
| **Arizona State University** | $427,358 | $108,380 | $421,782 | $101,607 | $849,140 | $209,987 |
| **Univ. of Cincinnati** | $339,002 | $85,858 | $339,988 | $88,824 | $678,990 | $174,682 |
| **MPT Inc.** | $371,678 | $92,920 | $371,750 | $92,938 | $743,428 | $185,858 |
| **Nexant** | $136,831 | $34,208 | $63,169 | $15,792 | $200,000 | $50,000 |
| **Total** | $1,274,869 | $321,366 | $1,196,689 | $299,161 | $2,471,558 | $620,526 |
| **Cost Share** | 80% | 21% | 80% | 20% | 80% | 20% |

Risks

Milestones

Success Criteria

# Risk Management

| Description of Risk | Probability | Impact | Risk Management<br>Mitigation and Response Strategies |
|---|---|---|---|
| **Technical Risks:** | | | |
| Multiple tube zeolite membrane synthesis does not result in membranes with hydrogen separation performance same as the single tube membrane | Low | High | Zeolite membranes will be fabricated tube by tube to meet the needs of main task on WGS membrane reactor development while more time will be spent on optimizing multiple-tube membrane synthesis method. |
| Initial 70-tube bench-scale module fails | moderate | high | Backup plan exists for making more zeolite membrane tubes and second or third modules. |
| **Resource Risks:** | | | |
| All facilities (hydrothermal synthesis, CVD modification, permeation test) require new establishment or significant modification that may cause delays | Moderate | Moderate | Depending on equipment vendor responses, facility establishment and modification may start earlier. |
| Lack of high pressure facility at ASU for testing bench-scale module as well as the intermediate scale modules | Moderate | Moderate | The membrane test skids will be set up earlier at NCCC, and the initial module tests will be conducted at NCCC. |
| **Management Risks:** | | | |
| Delays in hiring post-doc and graduate students | Moderate | High | Use current post-doc and graduate students to work on the project during interim. |

# Milestone Log

| Budget Period | Task | Milestone Description | Planned Completion | Verification Method |
|---|---|---|---|---|
| **1** | 2.3 | Completion of WGS in zeolite membrane reactor at pressures above 15 atm | 12/31/2016 (12 mo) | Report to DOE |
| **1** | 5 | Fabrication of 25 cm long zeolite membrane tube with $H_2/CO_2$ selectivity >45 and $H_2$ permeance >600 GPU | 9/30/2016 (9 mo) | Report to DOE |
| **1** | 6.2 | Fabrication procedures; 30 tube membranes with $H_2/CO_2$ selectivity >45 and $H_2$ permeance >600 GPU | 6/30/2017 (18 mo) | Report and membrane delivered to ASU |
| **1** | 8.2 | Fabrication and successfully test performance of WGS in the intermediate-scale membrane reactor | 6/30/2017 (18 mo) | Report to DOE |
| **2** | 12 | The bench-scale testing system is ready for operation. | 6/30/2018 (30 mo) | Shakedown operation report |
| **2** | 15 | Completing testing WGS in bench-scale zeolite membrane reactor with CO conversion >99%, $H_2$ recovery >92% and $CO_2$ capture >90%, $CO_2$ purity >95% | 12/31/2018 (36 mo) | Report to DOE |
| **2** | 16 | Completing design of commercial zeolite membrane reactor and techno-economic analyses of its integration with 550 MW IGCC plant | 12/31/2018 (36 mo) | Report to DOE |

# Success Criteria at Decision Point

| Decision Point | Date | Success Criteria |
| --- | --- | --- |
| **End of Budget Period 1 (end of first18 months)** | 3/31/217 | Success in testing WGS in 7 to14-tube intermediate scale WGS zeolite membrane module with membranes having<br>$H_2/CO_2$ selectivity >45<br>$H_2$ permeance >600 GPU and<br>operational at feed pressure up to 30 bar in 400-550$^oC$;<br>WGS membrane reactor achieves CO conversion >99%, $CO_2$ capture/ recovery >90% and $CO_2$ purity >95%. |


THANK YOU
ASU
Palm
Walk